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I act, therefore I err: EEG correlates of success and failure in a virtual throwing game

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ABSTRACT

What are the neural responses to success and failure in a throwing task? To answer this question, we compared Event Related Potentials (ERPs) correlated with success and failure during a highly-ecological-virtual game. Participants played a tennis-like game in an immersive 3D virtual world, against a computer player, by controlling a virtual tennis racket with a force feedback robotic arm.

Results showed that success, i.e. hitting the target, and failure, by missing the target, evoked ERP's that differ by peak, latencies, scalp signal distributions, sLORETA source estimation, and time-frequency patterns. The success related grand averaged ERP at the Cz electrode, had two peaks - a negative peak at 244 ms and a positive peak at 12 ms, prior to the actual successful hit, suggesting a possible process of prediction of success. The grand averaged ERP correlated with failure at Cz, had two peaks, a negative peak at about 107 ms and a positive peak at about 311 ms post failure. These results suggest different top-down and bottom-up loops for success and failure, which seem to be rooted in the spatial arrangement of the virtual game. Although the latency of the latter is consistent with the error related potentials reported in the literature, the characteristic is unique to this specific error, and differ significantly from other error related potentials in the same environment. These results further provide a basis for EEG based assessment and prediction of user's successful or erroneous movements, and design of the feedback loop in EEG based Brain-Computer Interfaces.

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1. Introduction

The motor system is crucial in all human action. Speech, gestures, writing, playing music, sports and surgery are just a few examples. Often, we err, even in performing a well-practiced act, and become ineffective. Is there a mechanism by which humans are capable of predicting an outcome of a motor act, especially failure or success? Indeed, human detection and correction of motor errors have been studied by modeling the behavioral, cognitive and neural correlates of performance. For instance, baseball players predict the outcome of a free throw shortly after the ball has left their hand, long before reaching the target (Maurer et al., 2015). In particular, studies of event-related brain potentials (ERPs) have shown the that motor errors correlate with a signal termed 'the error related potential' (ErrP) (Bediou et al., 2012; Maurer et al., 2015). Typically ErrP's are characterized by an early negative component followed by a positive component (Falkenstein et al., 2000). In this study, we look for ERP's that are uniquely correlated with erroneous and non-erroneous motor acts. We ask whether the characteristics of ERP's associated with errors differ from those correlated with success, then analyze the differences in order to identify whether any of these signals is predictive of the error/success. We previously found that failing to repel a ball in a virtual tennis game, was correlated with a unique ERP that had a flattened small negative component followed by a prominent positive component at ~450 ms. The success-ERP i.e. the ERP associated with correctly repelling a ball, differed by latency (~300 ms) and showed a more pronounced negative component (Yazmir and Reiner, 2016). Are these patterns typical of success and failure? Or, are they correlated with the unique spatial – motor stimuli of the error-context? Is the error/success ERP a generic signal i.e. are all errors/success events correlated with a similar ERP, or is the characteristics of the ERP dominated by the context in which the erroneous/successful act were performed? The importance is both in understanding the role of erring in mastering motor acts, and especially in designing the feedback loop in a BCI system. For instance, BCI targeting navigation with a wheel chair will be significantly enhanced, with strong and clear discrimination between success/failure ERP's, and especially if ERP's will support discrimination between type of errors, and allow an-error-tailored response loop. To study the nature of the error/success ERPs we looked at errors beyond catching/repelling, and focused on success or failure in achieving the goal of a virtual tennis-like game, i.e. resulting in hitting the target 'gate' in the game. We further ask if failing to repel a ball (as in Yazmir and Reiner, 2016) correlate with a similar ERP characteristics as failing to hit the target.

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To be able to compare, we used the same multisensory virtual environment as in the previous study, the same participants, yet we separated the epoch of each event to make sure that the ERP's are not carried over.

In the following sections, we describe recent studies on outcome errors, which provided the foundation for the current study.

Outcome errors occur when the movement goal was not achieved (Krigolson et al., 2008; Milekovic et al., 2012, 2013). For Instance, in a series of experiments with a continuous 2D motion task, electrical activity of the brain was recorded with electrodes placed directly on the exposed surface of the brain (known as Electrocorticography–ECoG). Participants used a joystick to control an external virtual agent that had to escape from falling blocks (Milekovic et al., 2012, 2013). The outcome errors occurred when the agent was hit by the falling blocks (Milekovic et al., 2012, 2013). Error related neural responses from the scalp in response to outcome errors, showed a distribution of peaks with a latency in the range of 100–800 ms after the error and a spectral response in the range of 0–4 Hz and in the range of above 40 Hz (delta and gamma bands respectively). The responses were located in the motor, somatosensory, parietal, temporal and pre-frontal cortex (Milekovic et al., 2012).

An ErrP study showed that for a similar experimental setup as above, it is possible to detect ErrPs related with outcome errors (Spuler and Niethammer, 2015). They further show that the outcome ErrPs have a central distribution peaking around FCz and Cz electrodes (Spuler and Niethammer, 2015).The outcome error related ErrP waveform had positive peaks at 268 and 742 ms, and negative peaks at 2 ms and 486 ms after the error had been made (Spuler and Niethammer, 2015). The spectral response to outcome errors included delta (1–4 Hz) at the vicinity of Cz electrode and theta at the Fz and FCz electrodes (5–7 Hz) bands (Spuler and Niethammer, 2015).

Prediction of an outcome error (referred to as commission errors) in a Go/No-Go shooting task, elicited a pre-error negativity potential (Bediou et al., 2012). During outcome errors, a fronto-central pre-error-negativity signal peaked at 91 ms prior to pushing a gun trigger, which possibly reflected a prediction of a future high error probability (Bediou et al., 2012). Research on continuous throwing tasks showed an error-negativity-like component with an onset of about 200 ms and a peak at about 250 ms after the ball release, and at about 600 and 550 ms respectively before the target was missed (Maurer et al., 2015). Another negative component with a peak at about 300 ms after and at about 500 ms before release was evoked and represented as a monitoring process (Maurer et al., 2015). These findings show varying error neural correlates depending on the context, task and conditions. However, in order to identify whether ERP's of success and failure are generic or depend on the task, it is crucial to keep all other conditions constant – the environment, constraints, sensory stimuli and participants. Hence, we look here at the ERP's associated with success and failure and ask whether patterns of ERP correlated with success are centrally different from failure, when we keep the environment, conditions, and participants constant, and then ask how the prediction power of each of the signals varies across error/success.

More specifically, the goal of the current study is to investigate ERPs related to throwing action outcome of success and failures, as the participant attempts to hit the gate, and score a goal in a continuous 3D virtual tennis game. A secondary task is to examine possible ERP correlates of throwing action outcome, then compare to previous results on success and failure in identical conditions, but different motor actions, in an attempt to test the genericity of error related potentials. In this experiment, “Hit” stands for success – (i.e. the player hit the ‘gate/target’ and scored a goal), and “Miss”, the player did throw the ball to the ‘gate/target’ and did not score a goal, stands for failure. We especially target the following questions: What are the ERP correlates of successful hits? What are the ERP correlates of failures, i.e. misses of the target/gate? What is the difference between them? Can these signals be used for action outcome prediction? Is it possible to acquire these signals during continuous 3D throwing tasks? Finally we ask what are the differences in ERP's of different motor errors when all other conditions are kept constant (Yazmir and Reiner, 2016).

A central factor in the experimental design is the reservation of ecological validity of the environment. Thus the experiment is designed to follow the experimental processes in interaction with the physical environment. Ecological validity is crucial to studying human behavior in the natural world, as it affects the timing of responses to sensory stimuli, similar to responses in the natural world (Sella et al., 2014) and enhances believability due to haptics (Frisoli et al., 2011). It seems that low ecological validity allows only limited transfer of results to real-life situations. To increase the validity of this study we designed a highly ecological valid experimental virtual 3D environment to evaluate possible real life ERPs correlated with prediction/recognition of successful or failing motor acts. The task required active planning and execution of a goal oriented motion for best performance. Results of this study may provide a basis for EEG based assessment and prediction of user's outcome acts – successful or erroneous, and its application as a feedback signal in EEG based continuous Brain-Computer Interfaces.

2. Materials and methods

2.1. Experimental system setup

The experimental setup (Fig. 1) is described in detail in Yazmir and Reiner (2016), and briefly summarized here. Using stereographic projection on a large half transparent glass, we created an immersive virtual space of about 82 × 55 cm. A Desktop Phantom haptic device (Geomagic, 2014) provided haptic feedback, thus the feel of the bat colliding with the ball was highly realistic. Motion was in all directions, with a position resolution is 0.023 mm and maximum force feedback of 7.9 N. While playing, participants were connected to a Biosemi 64 channel EEG recording system, 2 reference electrodes and 3 electrodes for Electrooculography (EOG). Two synchronized computers were used: for EEG recording and for the virtual reality processing. The lab environment was isolated, silent, darkened and comfortable.

Continuous EEG was acquired from 64 active Ag-AgCl electrodes, and sampled at 512 Hz. A 5th order anti-aliasing filter was applied with cutoff frequency at 102.4 Hz. Three EOG recording active electrodes were positioned above, below and on the left of the left eye. These electrodes measured signals related to horizontal and vertical movements of the eye and the eye's electrical activity. The signals were used for rejection of blinks and other ocular artifacts. Reference signals were recorded using a pair of active electrodes placed on the left and right earlobes.

The participants played a ball game that took place in a 3D virtual tennis court with walls, bottom floor and ceiling. The space had the shape of a huge box of size (66 W × 46 H × 180 D cm), and the ball was of 1.5 cm radius and virtual mass of 1 kg. The rackets were shaped as plates of size (2.6 W × 2.6 H × 0.05 D cm). Scores and remaining rounds were presented at the bottom of game space. The Phantom device was placed on a shelf beneath the half transparent glass, and was invisible to the eye of the player. Shortly after starting the game the participants felt as if their own hand was manipulating the racket (Christ and Reiner, 2014; Friedman et al., 2007; Raz et al., 2008; Reiner, 2004). Multimodality of both haptic and visual feedbacks have been shown to create a significant Stroop effect across modalities (Hecht and Reiner, 2010), in states of incongruence across modalities. Hence the game was designed to avoid such incongruences and reduce related EEG noise. Participants controlled the Phantom arm with their right or left hand alternately.

The physics of the virtual world followed the real-world physics laws and included: (1) Collision detection that allowed the ball to bounce from the walls; (2) Resistance force field with a maximum amplitude of 4 N was applied to the participant's hand and linearly decreased with the distance from the walls of the court; and (3) The momentum of the ball changed on collision with walls or rackets

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